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ABSTRACT

This information packet on quasars consists of an introductory paper, four articles from "Mercury," a journal of the Astronomical Society of the Pacific, and a bibliography. Methods used to measure distances in the universe and the nature of quasi-stellar objects (QSO's), the name preferred by many workers in the field, are discussed in the first article, "Cosmic Distances and QSO's" (Joe S. Tenn). Such areas as radio-quiet quasars, non-cosmological redshifts, absorption features in quasars, a quasar model, and the search for a plausible source of energy to power quasars are discussed in "Quasi-Stellar Objects" (Harding E. Smith). A brief history of quasars is also provided. The nature and probable cause of redshifts in quasars is the subject of "Quasars with Fuzz" (Bruce Balick). Phenomena associated with a particular quasar which may provide important clues to the understanding of quasars and their evolution are considered in "4C18.68: A Quasar with Precessing Jets" (Ann C. Gower and John B. Hutchings). A short bibliography of nontechnical books and articles is appended. (JN)

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Quasars:

Ancient, Awesome Violence

EXPLORING THE UNIVERSE

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Sherwood Harrington
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It will come as no surprise to astronomy enthusiasts that nature produces violent events in the universe. Some are of such awesome scale that they make nuclear bombs (or even some recent Hollywood movies) seem gentle by comparison--the "starbombs" of supernova explosions, for example, produce enough energy in a second to power a star like our Sun for a thousand years.

But it may well be the mysterious bodies called quasars which provide the ultimate in violence that nature has to offer.

Astronomers have known about quasars since 1963. In photographs taken with large telescopes, quasars look much like stars do: white dots on the picture, sometimes accompanied by a little faint fuzziness. (The name "quasar" is a contraction of "quasi-star," meaning "like a star.") Their appearance at first seemed thoroughly ordinary in a universe of stars--but their distances turned out to be astounding, even to astronomers. A typical quasar might be so far away that its light has taken ten billion years to reach us!

To put that in cosmic perspective, consider this: The image of the Moon reaches us in slightly more than a second, Pluto's in about five hours, the nearest star's in about four years, and the nearest other large galaxy's in about two million years. The light-carried news from our typical quasar takes 5,000 times longer than that.

This means, of course, that we see our typical quasar as it was well before the Earth was formed. It is a glimpse into the ancient history of the universe.

But the thing about quasars that gives astronomers goosebumps (and occasionally keeps them from sleeping well) is the simple fact that quasars can be detected at all. No "normal" body, like a galaxy or exploding star, produces enough light to be seen so clearly over such a vast extent of space. A rather simple calculation reveals that a typical quasar must be a thousand-fold more powerful energy producer than is our entire Galaxy.

So powerful, in fact, is a typical quasar that in a single second it produces as much energy as the Sun does in 30,000 years--indeed, more energy is unleashed in a quasar in one second than humankind has used in total throughout the history of the world.

In addition to their sheer power, quasars are perplexing because of their size: they are incredibly tiny in terms of the sizes of the galaxies they outshine. Quasars fluctuate, changing their brightnesses by large amounts over times of a few weeks, typically. According to astronomers, such rapid

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variation is possible only if the light-producing area of a quasar is small enough that light can travel across it in less than a few weeks. Galaxies are typically so large that light takes hundreds of millennia to cross them, so the quasars' powerhouses must be tiny in comparison.

So far, no completely satisfactory explanation for the source of quasars' prodigious energy output exists. Many exotic kinds of explosions have been considered, but all have been unsatisfactory in some way or another, at least to some degree. It is safe to say that quasars present a fundamental mystery in the science of large-scale energy generation

Still, a tentative model of what quasars are -- and what powers them -- is starting to gain acceptance among an increasing number of astronomers. The model involves a galaxy with a postulated mammoth black hole as its central feature: a region of space at a galaxy's core containing a hundred million times the mass of the Sun in a volume as small as our Solar System. This much mass packed so tightly would have such strong gravity that nothing, not even light, could escape from within it. But near the hole's outer limit -- a region from which radiation could still escape -- any infalling material would be so agitated, disrupted, and heated by the powerful gravity that it would radiate enormous amounts of energy outward into space. If there were enough such material being tortured, the brilliance of its radiation could well outshine the total of all the stars' in the galaxy whose core it is.

An interesting aspect of this model is that it requires vast amounts of material to "feed" the black hole and produce the radiant energy: interstellar gas or even stars being disrupted by the hole's gravity. Such material to "feed" the black hole would have been more common during earlier epochs in the history of the universe than it is now; a black hole is a one-way street, and eventually the energy-generating material around it will disappear. Indeed, astronomers now believe that any quasar still active today is being "fired up" by new material, perhaps from a smaller galaxy which has been captured by the one in which the quasar resides.

With that in mind, it's interesting to note that most of the quasars astronomers study probably don't even exist any more. Remember that our typical quasar was so far away that we were seeing light that left it billions of years ago. Dr. Maarten Schmidt, the astronomer who first discovered that quasars are very distant, has estimated that far fewer than one percent of all the quasars that were pouring energy into the universe ten billion years ago are still active today. In a sense, then, we can think of quasars as "cosmic dinosaurs" -- things which we can study only by their remains. We study the fossilized bones of real dinosaurs; we analyze the leftover light of quasars. And in both cases scientists have managed to use the past evidence to reconstruct some of the most awesome phenomena we have encountered.

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Cosmic Distances and QSO's

Joe S. Tenn
Sonoma State University

The next time you are out on a clear night, look around the sky. The brightest objects you see are likely to be the Moon and a planet or two; perhaps Jupiter will stand out. The other objects visible are stars in our galaxy.

A notable exception, if you are in a dark place and it is the right time of year, may be the oval blur which was long known as the Great nebula in Andromeda but is now more correctly called the Andromeda galaxy. Binoculars may help you find it.

The planets do not appear to be very different from the brighter stars, yet, as you may know, the stars are millions of times farther away. You may also be aware that the planets are hundreds to thousands of times more distant than the Moon.

Do you wonder how these distances have been determined? Certainly not with a tape measure. How reliable are they? Did you know that the estimated distance to the Andromeda Galaxy has almost tripled since it was first measured, just over half a century ago?

Let us examine the methods which have been used to measure distances in the universe.

Distances Within the Solar System

It is not surprising that the first distance to be determined was that of our nearest neighbor in space, the Moon. More than two thousand years ago, Ptolemy measured this distance by triangulation (also called parallax). He measured the angle formed by a point on the Moon and two points on the Earth's surface and "solved" the triangle by trigonometry.

You may wonder how Ptolemy managed to observe from two widely separated points on Earth. He simply waited a few hours, and the Earth's rotation carried him around to the other side.

Figure 1. The Hyades (photo by Miriam Carolin, Sonoma State University Observatory)

Ptolemy found, correctly, that the Moon's distance is fifty-nine times the Earth's radius. Today this distance, approximately 380,000 kilometers or 240,000 miles, is known to within a few centimeters. The greatest precision is obtained by measuring the round trip travel time of laser pulses sent from Earth to reflectors placed on the Moon by astronauts.

Many centuries were to pass before the distances to the planets could be determined. It was Copernicus, in 1543, who made the breakthrough. His famous book, *On Revolutions*, did more than just move the center of the universe from the Earth to the Sun; it also provided a scale model of the solar system. From the observed motions of the planets and geometry, the Polish canon computed the *relative* distances of the planets and Sun.

Copernicus found the average distances of the planets from the Sun in terms of the average distance between the Earth and the Sun, called the astronomical unit (A.U.); this turned out to be 0.36 A.U. for Mercury, 0.72 for Venus, 1.5 for Mars, 5 for Jupiter and 9 for Saturn. All that was needed was one direct measurement to set the scale.

This scale, which would allow us to convert from astronomical units to kilometers, has been measured with increasing precision over the past four hundred years. Today, an A.U. is known to be 149,597,870 km, or approximately 93 million miles. The best determination comes from the use of radar; echoes of radar signals have actually been detected from as far away as Saturn, nearly a billion miles away.

But nowadays we know that our solar system is, in a sense, merely our back yard. How did we obtain distances to the much more remote stars?

Stellar Distances

For centuries astronomers tried to measure stellar distances by trigonometric parallax. If the Earth actually moves around the Sun, then over the course of the year the nearby stars should show apparent motions with respect to the more distant ones, just as a pencil held at arm's length shows a shift relative to the background when viewed from one eye and then the other. The greatest pre-telescope observer, Tycho Brahe of Denmark, was able to measure angular changes as small as one minute of arc, yet he could detect no such motion. He concluded that the Earth does not move.

It was only 140 years ago that three different men, in three different countries, finally succeeded in measuring the yearly parallax of shift of three of the nearest stars. The first was Bessel, in Prussia, who measured the distance to 61 Cygni, a dim star suspected to be close to us because of its relatively large non-parallax motion across the sky. The others were Henderson, who observed Alpha Centauri from the Cape of Good Hope, and Struve, of Russia, who measured the shift of the bright star Vega.

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The parallax of a star is actually the angle through which the star appears to move as the Earth completes half of its annual orbit. Since the more distant stars will show a smaller parallax shift, the distance of the star is inversely proportional to this angle. Astronomers make things simple by measuring distances in *parsecs*, which are defined as the distance at which a star would have a parallax shift of one second of arc in each direction. One parsec turns out to be 206,265 astronomical units, or 3.26 light years. The nearest neighbor star to the Sun, Alpha Centauri, is one and one-third parsecs distant.

By now a few thousand of the nearest stars have had their distances determined by this direct geometric method. The brightest stars are not, in general, the nearest. Of the twenty brightest stars in the sky, only Alpha Centauri, Sirius, and Procyon are within five parsecs of the Sun. On the other hand, most of the nearest stars are intrinsically so dim that they cannot even be seen without binoculars or small telescopes.

If only a small fraction of the stars are near enough to have measurable parallaxes, and these do not even include some of the brightest stars, what do we do next?

One method of measuring the distances to more distant stars is based on the motions of stars in a nearby star cluster, such as the Hyades in the constellation of Taurus (Figure 1). Since our solar system is moving away from this cluster, all of its stars show motion toward a point on the celestial sphere, in a direction opposite that in which the solar system is moving.

If we assume that each star in the cluster is moving in the direction of this point at infinity, we can break up the star's motion into components along and perpendicular to our line of sight. The component along our line of sight can be measured directly in kilometers per second from the Doppler shift of the lines in the star's spectrum. Knowing the direction in which the star is moving, the component across the line of sight can then be determined, in kilometers per second, from geometry. It can also be measured, in seconds of arc per year (this is called the *proper motion*) from photographs taken years apart. Combining these two independent measurements yields the distance to the cluster.

We shall see that the recent revision of this distance changed the whole scale of the universe by nearly ten percent.

The reason this cluster is so important is that it provides us with a large number of stars with known distances. These stars can be plotted on a graph of luminosity versus spectral class, the well-known Hertzsprung-Russell (H-R) diagram.[1] Once the diagram is calibrated, with stars of known distance, it becomes possible to determine the distances of other stars by plotting their positions on the graph.

Since the basic position of the majority of stars in any cluster should be the same on such a graph, another cluster, of unknown distance, can be plotted on the H-R diagram, and the position of its stars adjusted so that its main sequence (the diagonal line where most stars fall on the diagram) coincides with that of the Hyades. The amount of adjustment necessary yields the distance to the cluster, in terms of the distance to the Hyades.

For example, if the main sequence stars in the Hyades appear 100 times as bright as similar stars in the other cluster, then that cluster is ten times as distant as the Hyades.[2]

A star need not be in a cluster for its distance to be determined by this method. Once its spectrum is measured and classified, it can be placed on the H-R diagram and its luminosity estimated. This was done for an enormous number of stars in the early years of this century. Foremost among the classifiers of stellar spectra was Annie J. Cannon, of Harvard College Observatory, who classified more than 300,000 stars.

Cepheid Variables

It was in 1912 that another of the Harvard astronomers, Henrietta Leavitt, made an important discovery. She was studying photographs made in South America of Cepheid variable stars in the Small Magellanic cloud. These are stars which regularly grow brighter and dimmer with a period of a few days or weeks.[3] Leavitt discovered a relationship between the periods of variations and the underlying luminosities of these stars. Of course she did not know their true luminosities, as the distance to the Small Magellanic cloud was unknown. But all that was needed was the distance of one Cepheid to calibrate the scale. Then the Cepheids, which are very bright stars, could be used as distance indicators.

Figure 2. Annie J. Cannon and Henrietta Leavitt (from Shapley, Harlow, Through Rugged Ways to the Stars, *Charles Scribner's Sons, New York 1969, reprinted courtesy of Willis H. Shapley.)*

Hertzsprung, Russell, and others used statistical methods to find the average luminosity of Cepheids, and then Harlow Shapley used Leavitt's relationship to measure the distances to the globular clusters. The result of his work was another Copernican revolution: Copernicus had showed that the Earth was not at the center of the the solar system. Now Shapley showed that the Sun was not at the center of the system of stars. The globular clusters surround the Galaxy, a disk some 100,000 light years across and the Sun is off to one side.

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1. An H-R diagram is depicted on p. 126 of the Nov/Dec 1978 *Mercury*. It is also available on a new A.S.P. T-Shirt, as described in the *Selectory* in this issue. — *Ed.*

2. This calculation follows from the fact that the intensity of light falls off as the *square* of the distance. — *Ed.*

3. See the article on variable stars by John Percy in the May/June 1979 *Mercury*. — *Ed.*

Figure 3. Robert Hanson accepts the 1976 A.S.P. Trumpler Award from then-president Geoffrey Burbidge.

Shapley, however, made an important error regarding the fuzzy objects which were then called spiral nebulae. He thought they were small, nearby objects, either satellites of the Milky Way or perhaps objects which filled the space through which the Galaxy moved.[4]

It was Edwin Hubble, just over fifty years ago, who showed that the spirals were actually external galaxies comparable to the Milky Way. He did this by finding Cepheid variables in some of the nearer spirals, most notably the great one in Andromeda. He found this object to be 285,000 parsecs, or about 900,000 light years, distant. (Today it is believed to be about two and a half times as far away.)

Hubble and Milton Humason went on to measure the distances of more than thirty galaxies in this manner. They then proceeded to measure more distant ones by using their brightest stars as *standard candles*. They reasoned that if the brightest star in each galaxy had about the same intrinsic brightness, then the dimmer such a star looked in a given galaxy, the more distant that system had to be.

Finally, they used the brightest galaxies in clusters as distance indicators. On the average, at least, the dimmer galaxies should be farther away.

From all this work they were able to make a most important discovery: the velocity-distance relation, now usually called the "Hubble Law." It states that all but the nearest galaxies are receding from us and that the velocities of recession are proportional to their distances.[5] The velocities of recession are calculated from the *redshifts*, or fractional increases in wavelength of the spectral lines. Knowing the velocity, astronomers can then use Hubble's Law to calculate the distance to galaxies so remote that neither individual stars or clusters can be discerned in them.

With long time-exposures, large modern telescopes can detect enormous numbers of galaxies. It is estimated from counts of a few random areas that if one could spend the necessary thousands of years photographing each section of the sky, then more than a billion of them could be detected. Indeed, deep photographs show more galaxies than stars! Most of these are too faint for detailed examination, but the dimmer ones do show larger redshifts, indicating greater velocities of recession. They appear to obey the Hubble Law. Thus today a galaxy with a certain measured redshift is taken to be at the distance given by this law.

For many years, from 1960 until the mid-1970's, the most distant galaxy known was 3C 295, the radio galaxy whose redshift was measured by Rudolph Minkowski on the last night he was allowed to use the Hale telescope before compulsory retirement at age 65. Its redshift of 0.46 corresponds to a distance of 2 billion parsecs or 6.5 billion light years. In recent years the use of electronic photon detectors on large telescopes has allowed Hyron Spinrad and others to measure several galaxies with redshifts of 0.6, 0.7 and even higher. One galaxy, called C1 1305+2952, has a redshift of 0.947.

Deviations from the Hubble Law, expected for very distant galaxies, should in principle allow us to determine the geometry, and hence the fate, of the universe. However, there are great problems in determining the effects of the evolution of galaxies.[6] Let us return therefore to the measurement of distances.

Revisions in the Scale

The distance scale built up until now has been revised three times. In the 1930's, Robert Trumpler showed conclusively that there is an "interstellar smog." Thus some of the dimming of stars is caused by the passage of their light through dust in our galaxy rather than by distance as previously assumed. In addition, it was shown in the 1940's that there are actually two kinds of Cepheid variables, with different period-luminosity relations. Both of these discoveries increased distance estimates.

The third revision came in 1976 when Robert Hanson, a graduate student at the University of California, Santa Cruz, showed by the old-fashioned measurement of proper motions that the Hyades cluster is

4. A famous debate on this subject between Shapley and H.D. Curtis was described in the Jul/Aug 1978 issue of *Mercury*. — *Ed.*

5. The equation is written V = Hd, where V is the velocity, d is the distance and H is called Hubble's constant.

6. See "Cosmology — The Origin and Evolution of the Universe" in *Mercury* May/June 1978. — *Ed.*

actually farther away than previously thought. Since all distances are built up from the location of the main sequence of this nearest cluster, the demonstration that it is 144 light years away rather than 132 was sufficient to increase the known size of the universe nearly 10%![7] Another way of stating this is that the best estimate of the Hubble constant dropped from 55 kilometers per second per million parsecs to 50. (The earlier revisions had brought it down from Hubble's original value of more than 500.)

Quasars

What are quasars? In short, we don't know. These *quasi-stellar objects* (a name preferred by many of the workers in the field) look much like ordinary stars. It is only when one examines their spectra that their strange properties appear.[8]

These objects, which look like blue stars, have the largest redshifts known. They range up to 350% for two discovered in 1973, with many shifted by 100 to 200%.[9] With these, we are back in the position of the astronomers of 150 years ago looking at the stars, or those of 60 years ago, looking at the spiral nebulae. We don't know how far away they are; we really do not know much about them at all.

In the sixteen years since the quasar's large redshifts were discovered by Maarten Schmidt at Caltech, there has been no lack of effort by theorists to explain the QSOs. The most natural explanation to most astronomers and physicists is that the redshifts are Doppler shifts, like those of the galaxies. One of the best reasons for this assumption is that there is no other explanation. Gravitational redshifts[10] have been shown to be unlikely and no other causes of redshifts are known.

Once we assume the redshifts are Doppler shifts, we have the problem that the QSOs are all moving away at speeds comparable to the speed of light, over 90% for two of them. Why are they moving away so fast? If they are nearby, they must have been ejected by our own or other nearby galaxies. The problem with this is that there are too many quasars. A recent estimate gives seven per square degree in the sky brighter than twentieth magnitude. Even though we do not know their masses, it seems that too violent an explosion is required in this part of the universe.

Figure 4. Galaxy NGC 4319, redshift 0.006 and companion quasar Markarian 205, redshift 0.07 (Arp, H., Astrophysical Letters 9,1 (1971).

There is also the problem that QSOs would have to be ejected from other galaxies as well, and some should be coming our way. Yet, no blue shifts have been found.

Thus it is not surprising that most astronomers have made the assumption that the quasars are obeying the Hubble Law, sharing in the expansion of the universe. This, of course, places many of them out beyond the most remote galaxies yet detected, and leads to newspaper headlines: "Most distant object discovered" or "Oldest thing in the universe found." Since the quasars appear to be up to ten billion light years distant, it follows that their light has been traveling for as much as ten billion years, and we see them as they were when the universe was young. In fact, one of the arguments for an evolving universe is that there are too many quasars with large redshifts and too few with small ones. This implies that the density of quasars in the universe was greater some billions of years ago than it is now. Hence, the universe is changing.

It is popular to believe that the quasars are some kind of early stage of galaxies. It is even thought that the Seyfert galaxies, with their bright star-like nuclei, provide the "missing link."

So why isn't everyone happy, except, of course, those cosmologists who do not accept the idea of an evolving universe? The problem is that the quasars appear to be too bright to be so far away. Putting in the distances given by the Hubble Law, and the apparent brightnesses, and using the inverse square law, we find that the quasars are 100 to 1000 times as bright as the brightest galaxies.

You might say that perhaps quasars are bright for a short time and then evolve into galaxies. While some people do say this, there is the additional problem that the quasars are known to be small. They vary in brightness in times as short as months. This means they cannot be more than light months across, a diameter not much bigger than the solar system.

The arguments have raged for more than a decade now. The steady state cosmologists, especially Geoffrey Burbidge, have argued that the quasars must be nearby, and that the redshifts cannot be cosmological Doppler shifts. Is any progress being made?

On several occasions each side has claimed victory. For example, in 1973, it was asserted that quasars, like galaxies, obey a Hubble Law: the dimmer ones have the larger redshifts. While a plot of redshift versus magnitude (dimness) for a large sample of quasars does not show this relationship, G. Setti and A. Woltjer found one by dividing quasars into three groups: those with no radio emission, those with flat radio spectra and those with steep radio spectra. Only in the third group were they able to find a tendency towards larger redshifts for dimmer objects.

Others have said that the only reliable way to determine the distances to these mysterious objects is to show

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7. For this work Dr. Hanson received the 1976 Robert J. Trumpler award of the A.S.P. — *Ed.*

8. See the article on quasars by H.E. Smith in the Mar/Apr 1978 issue of *Mercury*. — *Ed.*

9. These redshifts can be greater than 100% because at such high speeds Einstein's theory of relativity comes into play, as explained on p. 27 of the Mar/Apr 1978 *Mercury*.

10. Gravitational redshift is the change in the wavelength of radiation in a gravitational field. It is only detectable when the source has a very strong gravitational field. — *Ed.*

Figure 5. Galaxy NGC 1199, and compact companion. (Arp, H., Astrophysical Journal 220, 401 (1978). (Courtesy of H. Arp and the Astrophysical Journal, published by U. of Chicago Press, © 1978, AAS.)

that they are attached to objects whose distances are known. The only other objects around are the galaxies, so great efforts have been made to photograph quasars near galaxies and to find links. Foremost in this field has been Halton C. Arp of the Hale Observatories. Over the last decade he has photographed a great number of peculiar objects and claimed to see connections between objects of different redshifts.

Figure 4, for example, shows a galaxy, NGC 4319, with a redshift of 0.006 and a quasar, Markarian 205, with a redshift of 0.07. If both obey the Hubble Law, the quasar is more than ten times as far away as the galaxy, and their appearance in the same part of the sky is purely a coincidence, like the case of Alcor and Mizar, the well-known double star in the handle of the Big Dipper. In the picture, which is greatly over-exposed and taken through a filter, Arp sees a physical link.

Arp believes that quasars are ejected from galaxies, and that they have redshifts which have nothing to do with velocity but rather are intrinsic and change with time. He has presented a great number of examples of ejection in a series of papers over the past dozen years.

A debate about these issues, between Arp and John Bahcall of the Institute for Advanced Study, was held in Washington, D.C. in December 1972.[11] This recalls the famous debate between Harlow Shapley and Heber Curtis on "The Scale of the Universe." Both debates are enjoyable to read, but observations rather than debates are needed to settle scientific controversies.

In 1978 the situation became even more exciting. In March, Arp published an astonishing photo (Figure 5) in the *Astrophysical Journal*. It shows an elliptical galaxy, NGC 1199, with a small, compact object apparently *silhouetted in front* of it. Notice the dark ring (light in this negative print) around the small object. This can only be absorption of light from the larger galaxy by a shell of gas and dust around the small object. Arp presents a detailed discussion showing that everything is consistent with this hypothesis. Yet the redshift of the small object corresponds to a velocity of over 13,000 km/sec while that of the elliptical galaxy implies that it is receding at only 2600 km/sec. Arp concludes his paper:

> This is interpreted to be another example of a young, compact object recently ejected from the E galaxy and having a moderate component of intrinsic, non-Doppler redshift.

Shortly afterward, Alan Stockton of the University of Hawaii published an article in the same journal purporting to prove that the redshifts of the quasars *are* cosmological

What Stockton did was to survey a complete sample of quasars in a certain range of magnitude, redshift, and location in the sky. He chose all those from a certain catalog which were visible from Hawaii and had redshifts low enough that galaxies with the same redshifts should be visible. In other words, these are relatively low redshift quasars, with redshifts of 0.2 to 0.44. For each quasar, he measured the spectra of all galaxies within 45 seconds of arc in the sky. He was able to obtain redshifts for 25 of the 29 galaxies within 17 fields. Thirteen of these, in eight of the fields, had redshifts essentially the same as those of the nearby quasars. This implies that the quasars are members of clusters of galaxies and that their redshifts are in fact due to their motion away from us. He states that:

> The probability that this number of agreements is due to chance has been evaluated from the observed distribution function with redshift of the galaxy sample, and has been shown to be less than 1.5×10^{-5}, making the cosmological nature of QSO redshifts virtually certain.

By now you should be confused. Who is right? Are the quasars sharing in the expansion of the universe, making them the most distant objects detected and puzzling only because of their enormous energy outputs, or are they much nearer, teasing us with redshifts which are not due to velocities but to some "new physics" yet to be discovered?

I don't know, but I believe that, as in the case of the stars a few centuries ago and the spiral nebulae a few decades ago, their nature will become understandable only after their distances are determined. ■

Astronomy Hotline 415-661-0500

The Astronomical Society of the Pacific has a "hotline" telephone number to call for up-to-date news from the world of astronomy. The tape features a two-to-three minute recording with one interesting item of news, culled by A.S.P. Projects Coordinator Sherwood Harrington from university and observatory news releases, published news items, and reports of conferences. The message is changed weekly and is written with a layperson caller in mind.

The number (415-661-0500) can be called 24 hours a day and is located at the Society's headquarters in San Francisco. Callers from other parts of the country and the world might consider calling late in the evening, when rates are low and the line is less likely to be busy.

Quasi-Stellar Objects

Harding E. Smith
University of California, San Diego

Quasars — the most distant, the most energetic objects known in the universe. At least, this is the view of many astronomers. Yet the discovery of quasars has spawned one of the most active astronomical debates since Harlow Shapley and Heber Curtis debated the nature of the spiral nebulae. This debate has many facets, primary among them the question of whether these puzzling objects are relatively nearby or instead lie at incredibly great distances from us.

If quasars are as distant as many astronomers believe, then they must be the most luminous objects in the universe. What then could be the source of their tremendous power at radio, infrared, visible and even x-ray energies? Although the first quasar was identified nearly twenty years ago, it may not be unfair to say that, while we know much more about the properties of quasars today, we do not really understand a lot more about these fantastic objects than we did when they were first discovered.

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A Brief History

In the late 1950's, radio astronomers believed that celestial sources of radio noise are associated either with galactic nebulae, such as supernova remnants and ionized hydrogen regions, or with giant active galaxies, such as the radio galaxies Cygnus A and Centaurus A. Weak radio emission had been detected from the Sun, but it was recognized that this sort of radio emission was much too weak to be detected even from the nearest stars. It was thus something of a surprise when in 1960 Allan Sandage discovered a blue star-like object on a photograph he had taken with Palomar's 200-inch telescope. The position of this object coincided with the radio source 3C 48 (the 48th source in the third list of radio sources compiled by radio astronomers in Cambridge, England). Even though the object identified with 3C 48 appeared star-like, its radio emission meant that it clearly could not be a star. Hence the term quasi-stellar object (or QSO) was coined and later shortened to quasar. Shortly thereafter Cyril Hazard and his colleagues obtained a very accurate position measurement for the radio source 3C 273, by observing the exact time that the radio signal disappeared and reappeared as the moon passed in front of the source. This precise measurement enabled Hazard's group to identify a second even brighter "star" with 3C 273.

When these "stars" were studied with spectrographs (instruments which spread their light into the component colors), it became clear that they were indeed very peculiar objects. The optical spectra of both 3C 48 and also 3C 273 (see Figure 1, for the latter) showed strong broad emission features which could not be readily identified. Such features (also called emission "lines") had been seen in the spectra of certain types of hot, luminous stars called Wolf-Rayet stars. But the wavelengths of the features in 3C 48 and 3C 273 did not correspond to the wavelengths of the features seen in Wolf-Rayet stars, nor were the features in 3C 48 at the same wavelengths as those in 3C 273. Maarten Schmidt eventually recognized that the features in the spectrum of 3C 273 looked just like the pattern produced by hydrogen (Balmer) emission, but shifted by an unexpected 16% toward the redder colors (longer wavelength). It was then immediately seen that the features in the optical spectrum of 3C 48 could also be identified if they were "redshifted" by 37% (or 0.37, as astronomers generally write it.)

The shifting of the wavelengths of light is not unique to the quasi-stellar objects. By 1963 galaxies had been found with redshifts as large as 0.46. In fact, a well-established principle of physics demands that light from *any* object that is moving away from us be shifted toward the red by an amount that depends on the object's velocity. (If the object is moving in our direction, the shift is toward the blue.) The redshifts of 3C 273 and 3C 48 then correspond to velocities away from the Earth of 15% and 30% of the speed of light, respectively.

The redshifts found for galaxies are due to the general expansion of the universe. Because of this expansion, galaxies which are farther away from us are moving away more rapidly and therefore have higher redshifts. In fact, according to a rule first discovered by Edwin Hubble, the distance of a galaxy is directly proportional to its velocity. Therefore, once the velocity (or redshift) of a galaxy is measured one need only multiply it by a constant (called Hubble's constant) to find its distance.[1]

The surprising thing about 3C 48 and 3C 273 was not really their enormous redshifts, but their radio and visible brightnesses. 3C 273 (despite its star-like appearance) has more than fifty times the brightness that even the brightest supergiant *galaxy* would have if it were at the distance corresponding to a redshift of 0.16 (about 3 billion light years). If quasars are as distant as one would infer from their large redshifts, then they must be the most luminous objects ever discovered!

Since 1963 many more quasi-stellar objects have been discovered, many with even higher redshifts. The highest-redshift quasar (listed in the *Guinness Book of Records* as the "most distant object in the universe") is the object associated with the Ohio radio source OQ 172. A team of astronomers, using the University of California's 3-meter telescope at Lick Observatory showed that this object has a redshift of 3.53.[2] The features in the spectrum of this quasar are shifted by a factor of over four and a half in wavelength, so that light emitted by the quasar at far ultraviolet wavelengths is shifted into the visible region of the spectrum. This large redshift implies that OQ 172 is moving away from us with a velocity of more than ninety percent of the speed of light. If one

[1] For more about the expansion of the universe, see the article by James Gunn in *Mercury*, Nov/Dec 1975.

[2] This number is greater than one, because at such enormous speeds the formula which relates redshift and velocity must include the effects described by Einstein's theory of relativity. The full formula is:

$$\text{redshift} = \sqrt{\frac{1 + (\text{velocity}/\text{speed of light})}{1 - (\text{velocity}/\text{speed of light})}} - 1$$

However, when the speed (and, therefore, redshift) is small, this formula reduces to:

redshift ≈ velocity/speed of light

Thus a redshift of 0.16 means a velocity of 15% the speed of light; but a redshift of 3.53 does *not* mean a speed more than three times greater than the speed of light.

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considers that the "edge of the universe" is the distance that light could have traveled during the time since the "Big Bang" when the universe began its expansion (about 20 billion years ago) then, OQ 172 must be nine tenths of the way to the edge of the universe! This also means that the light we are now receiving from OQ 172 was emitted about 18 billion years ago, at a time when the universe was very young: galaxies were presumably still in the process of settling down after condensing out of the intergalactic medium, and star formation must have been proceeding very vigorously.

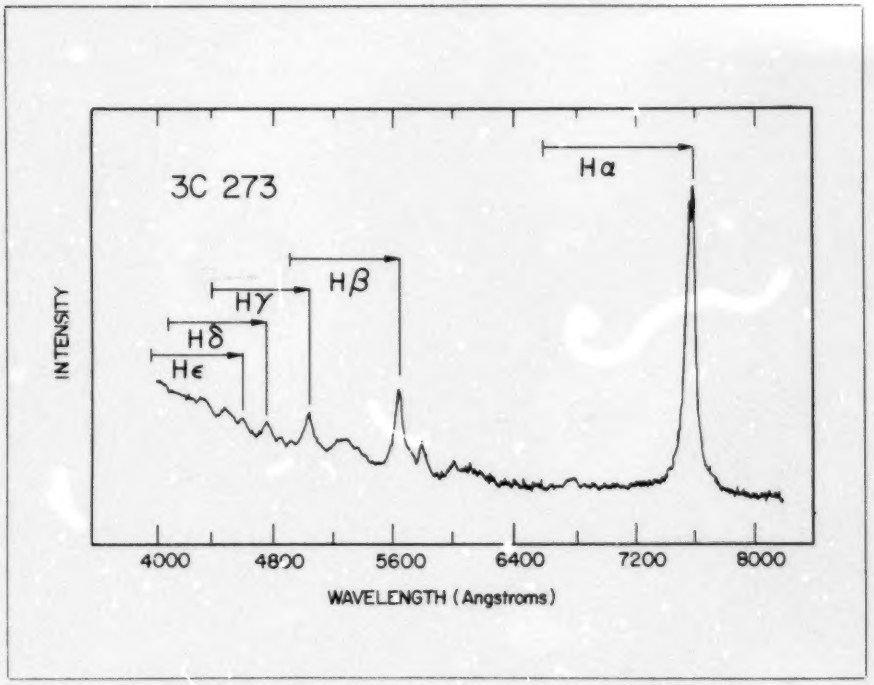
Radio-quiet Quasars

While the first quasi-stellar objects were discovered by their powerful radio emission, not all quasars are radio sources. In fact, there appear to be about fifteen times as many "radio-quiet" quasars as there are radio emitting ones. These radio-quiet quasars have been discovered by two methods:

1) Many quasars, because of the nature of their optical spectrum, have an excess of light at ultraviolet wavelengths relative to the blue, green, and red, when compared with normal stars in our galaxy. (White dwarfs, because of their very high atmospheric temperatures have a similar "UV excess"). It was this ultraviolet excess that first allowed astronomers to find the radio-quiet quasars among the thousands of stars with the same appearance on astronomical photographs.

2) Not all quasars have an ultraviolet excess, however. This is especially true for high-redshift quasars, so a new technique has been developed which is especially effective in finding quasars with redshifts greater than about 1.75. At these redshifts, the very strong hydrogen emission feature called Lyman α (whose unredshifted wavelength is 1216 Angstroms[3] and which is usually seen in the ultraviolet) is shifted into the visible region of the spectrum. By placing a prism in the wide-field cameras used for taking astronomical photographs, one can get, instead of simple star images, a photograph of the spectrum of all the objects in the field of view. Even though these spectra are tiny and have very low resolution, the Lyman α emission is strong enough for high-redshift quasars to stand out on these prism photographs. Although this technique should reveal quasars with redshifts as high as 5, it remains a puzzle that no quasar with a redshift greater than 3.53 has yet turned up among the hundreds of quasars that have been found using the technique.

Despite these two effective techniques for finding radio-quiet quasars, we still do not have a very good handle on the total number of radio-quiet quasars compared with those that are radio sources. It is possible that there are types of quasars which these methods fail to find, for example, low-redshift quasars without UV excess.



1. The optical spectrum of the quasar 3C 273; intensity of light is plotted against wavelength (blue to the left, red to the right). The strong hydrogen Balmer emission features stand out. The arrows show where the feature would appear in unredshifted objects and indicates how far the redshift for 3C 273 (0.16) has shifted them. (Illustration courtesy of J. Baldwin and **The Astrophysical Journal**, *published by the University of Chicago Press; © 1975 The American Astronomical Society.)*

Further Problems

In addition to the problem posed by the extremely large luminosities of the quasars, two additional observations have complicated the situation still further. The first is the discovery of highly variable quasars. Nearly all quasars' visible light output varies by small amounts over a period of a few months. Some quasars, however, vary in brightness by a factor of two or more; in a time as short as a few weeks. One such object, 3C 279, has been noted since its discovery in 1965 for its high variability. In addition, by looking at the series of photographs in the Harvard patrol plate collection which covered that region of the sky, Harvard astronomers discovered that 3C 279 had produced an incredible outburst in 1936 and again in 1937. (See Figure 2.) The old plates showed that over a period of about 4 weeks, 3C 279 had brightened by a factor of 25! Because the time needed for light to cross the light-producing region would smear out such variations if the emitting region were very large, these variations imply that the emitting region must be smaller than a few light weeks.

To understand how we arrive at this conclusion, consider three regions in a quasar which simultaneously emit a burst of light. (See Figure 3.) If the distance between points 1 and 2 and between points 2 and 3 is one light week in each case, then the light emitted from point 1 will reach point 2 one week after point 2 has emitted its light. Light from point 1 will reach point 3 two weeks after point 3 emitted its burst. As a result, we will receive the light from point 3 two weeks before we receive the light from point 1. The simultaneous outburst will thus appear to us to have taken two weeks. Of course, the outburst would be spread out even more in time if the source were larger. Thus the fact that we see outbursts lasting a few weeks implies that the quasar cannot be any larger than a few light weeks, (but of course it could be much smaller). Incredibly, these "most luminous objects in the universe" produce all their energy in a region that is a tiny fraction of the distance from the Sun to our nearest stellar neighbor, Alpha Centauri!

Even more perplexing perhaps are those few objects with radio sources in their centers that appear to be expanding with a velocity greater than the velocity of light! One of these is 3C 279 and another is 3C 120, not a quasar, but apparently an active galaxy. In 1972 and 1974 outbursts occurred in a compact radio source centered on the nucleus of 3C 120 (See Figures 4 and 5.) In each case the source has been seen to

[3]One Angstrom unit is 10^{-10} meters.

expand continuously for several weeks. If one uses the distance to 3C 120 that its redshift of 0.033 implies (200 million light years), one can calculate that the source was expanding at velocities of 3.5 and 7 times the speed of light respectively), for the two outbursts. Of course, this is impossible under Einstein's special theory of relativity, which states that no objects can move more rapidly than light. It has been suggested that certain configurations of a source expanding at nearly the speed of light might show *apparent* expansion at speeds greater than the speed of light (without anything really moving that fast), but no satisfactory model of this type has yet been worked out in detail.

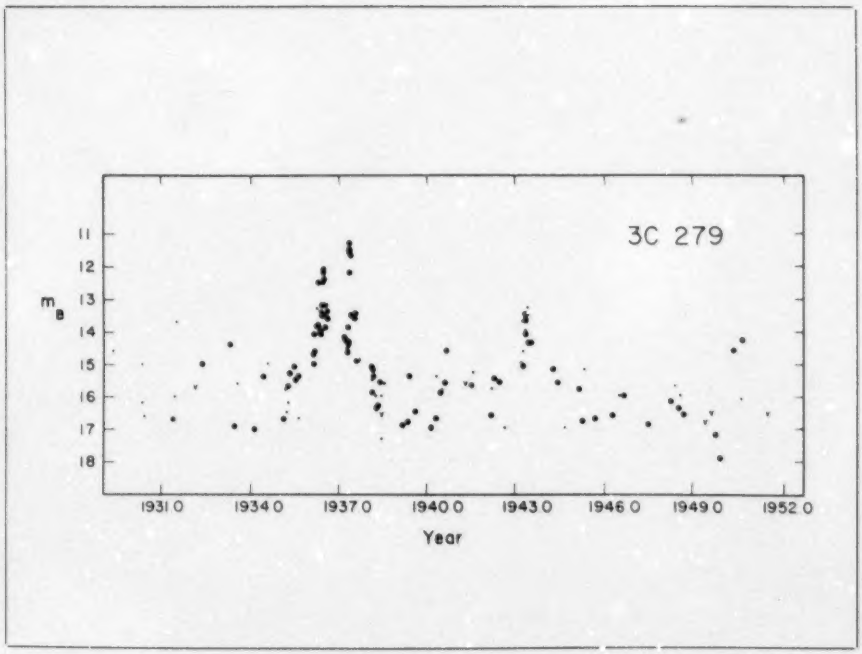
"Noncosmological" Redshifts

The problems of the extreme luminosity of the quasars and their apparent super-relativistic[4] expansion would disappear if the quasars are much closer to us. For this reason, many astronomers have considered the possibility that the redshifts of the quasars are not a true indication of their distances. The redshifts would then be "noncosmological," because they would not be produced by velocities due to the expansion of the universe, but by some other process.

If the redshifts are not the result of the expansion of the universe, then what could produce these shifts? James Terrell has suggested that quasars could be massive stars ejected at relativistic velocity from the nucleus of our galaxy by an explosion hundreds of millions of years ago. If this were the case, then one would expect to see blueshifts for some objects, either for those that are still coming in our direction from the nucleus of our galaxy or perhaps for quasars ejected from similar explosions in nearby galaxies. To date, despite active searching, no significantly blueshifted objects have been detected.

The only other currently known mechanism which could produce a redshift is the action of a strong gravitational field. Light must lose energy in escaping from the gravitational attraction of a massive object. This loss produces a shift toward the red region of the spectrum — which carries less energy than the bluer (shorter wavelength) light waves. Light escaping from the Earth receives an almost imperceptible redshift, but light escaping from a very massive compact object can be redshifted by a very large amount. For example, light originating one light week from an object whose mass equals 12 billion solar masses would be redshifted by 10% in escaping from its gravitational field. Gravitational redshifts have been detected in white dwarf stars and in radio transmissions passing close to the Sun from spacecraft.

At first, this mechanism seemed an attractive possibility to explain quasars' redshifts. However, a simple argument can demonstrate that strong gravitational fields



2. The brightness of the quasar 3C 279 between the years 1931 and 1952 as determined by L. Eachus and W. Liller from the Harvard College Observatory plate files. Large outbursts occurred in 1936 and 1937. The strong light variability in relatively short times indicates that 3C 279 must be smaller than a few light weeks in size. (Illustration courtesy of L. Eachus and W. Liller and **The Astrophysical Journal**, *published by the University of Chicago Press; © 1975 The American Astronomical Society.)*

are unlikely candidates for the job. Since the gravitational field strength decreases with the distance from a massive object, light produced in different regions, at different distances from a central source, will be redshifted by different amounts. Since we know that the emission features of different atoms must indeed be produced in different regions, we would expect these features to show different redshifts. Yet observations indicate that all emission features generally show the same redshift in a given quasar.

If the redshift is not the result of velocity or of a strong gravitational field, then it will be necessary to devise a new physical mechanism to produce redshifts. The necessity for "new physics" has been a strong deterrent to many scientists in considering the possibility of noncosmological redshifts seriously, despite the severe physical problems in explaining the quasars' luminosity and variability. Still, some evidence has been presented which many believe suggests that at least some quasars are closer than their redshifts would indicate.

It is important to realize that outside our own Local Group of galaxies the redshift provides the primary indicator of distance for astronomers. Thus it is very difficult to establish that an object is *not* as far away as its redshift indicates. One way to show this would be to establish a physical connection between two objects with different redshifts. If we could show that two (or more) objects were at the same distance, but had very different redshifts, than at least part of the redshift of one of the objects would have to be "noncosmological." A number of possible cases have been presented: One example is the "double quasar" 1548+114. In 1973, astronomers at Lick Observatory discovered two quasars, one a radio source, the other radio-quiet, which appeared very close together on photographs. (See Figure 6.) The radio source has a redshift of 0.436, while the radio-quiet quasar has a redshift of 1.90, suggesting that it must be considerably farther away. Yet one can calculate that it is extremely unlikely for these two quasars to appear so close to one another by chance. Alan Stockton of the University of Hawaii later measured the redshifts of a group of faint galaxies close to the quasar pair. He found that these galaxies have redshifts very nearly equal to that of the low-redshift radio source. Since most astronomers believe that *galaxy* redshifts *are* a good distance measure, this suggests that the radio quasar is associated with the galaxies, and has the distance that corresponds to a redshift of 0.436 (about 7 billion light years). But what of the radio-quiet quasar with a redshift of 1.90? Many astronomers point to the fact that we do not really know how many radio-quiet quasars exist; if there are many more than

[4]The term *relativistic* refers to speeds close to the speed of light; *super-relativistic* implies velocities greater than light speed.

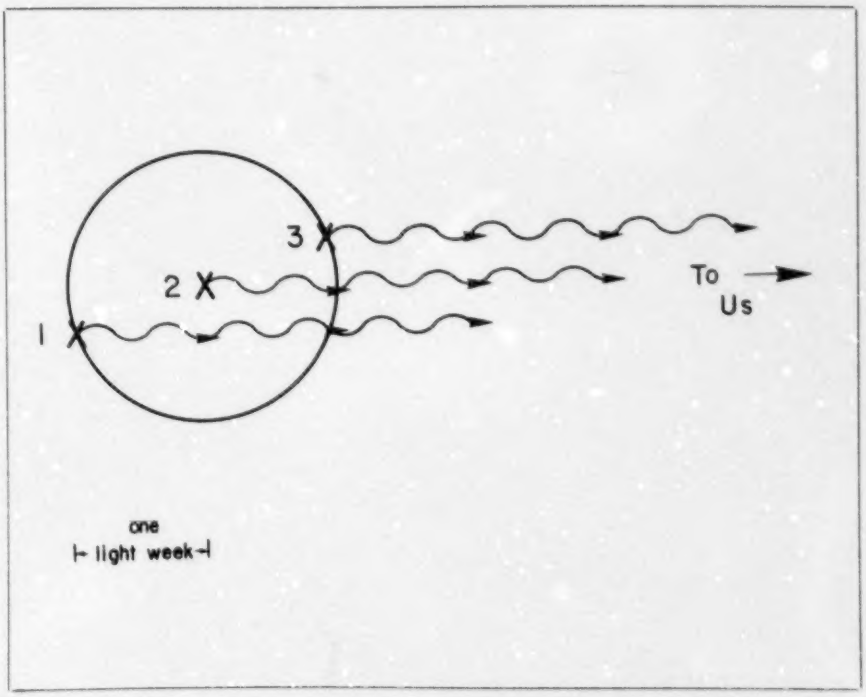
previously believed, then the chance occurrence of unrelated quasars close together on the sky would not be so rare.

The most active proponent of the "noncosmological" redshift is probably H. C. Arp of Hale Observatories (see the interview in *Mercury* Nov/Dec 1974). Arp has found a number of similar cases: quasars with high redshifts that appear close to bright galaxies, or objects with very different redshifts that appear quite close together. In some cases, Arp believes he has even found material connecting objects of very different redshifts. While in any given case it is quite difficult to prove that two objects with different redshifts are physically associated, the number of these cases that Arp has discovered is difficult to explain away.

On the other hand, some quasars *do* appear to be at the distances implied by their redshifts. Several low-redshift quasars have now been found to be members of clusters or groups of galaxies which have the same redshift as the quasar. Again, it is the statistical argument (that the chance that a quasar would accidentally appear so close to a group of galaxies with the same redshift is very small) that "proves" the association. However, only for the low-redshift quasars have such associations been detected, since at redshifts greater than a few tenths, galaxies are too faint to be detected with our present telescopes.

Even more suggestive is the recent work by Joseph Miller of Lick Observatory, who has detected very weak features caused by *stars* in the spectra of a few quasars. The stellar features are very weak because of the very bright contaminating quasar spectrum, so extremely painstaking observations are required. Nevertheless, Miller's work implies not only that these quasi-stellar objects are associated with galaxies at the same redshift, but that the quasars are embedded in galaxies. This supports the popular theory that quasars are active events in the nuclei of other galaxies, similar to the central parts of Seyfert galaxies and other active galaxies, which may then be considered "mini quasars."[5]

While those who favor the cosmological explanation of quasar redshifts are currently in the majority, the proponents of noncosmological redshifts continue to find perplexing examples of possible associations between objects with different redshifts. It would be safe to say that the question has by no means been resolved.



3. Extended light sources "smear out" variability because of the light travel time between different emitting regions. If a quasar were to emit a single burst of light, then the radiation from points 1, 2, and 3 would reach an observer at one week intervals. Thus this single outburst would appear to take two weeks. Hence quasars which show substantial variability in times of a few weeks cannot be larger than a few light weeks in size, otherwise the variations would be smeared out over even longer times.

Absorption Features in Quasars

Besides their strong emission features, quasars, particularly those with high redshifts, also show *absorption* features in their spectra. In fact some quasars show hundreds of absorption features in the region of the spectrum observed by optical astronomers. One sees so many absorption features in some objects that it is virtually impossible to identify them all. The features that can be identified are often some of the same features seen in emission in quasars, but not at the same redshift. The absorption features in a given quasar typically appear at a smaller redshift than the emission-line redshift and often there are many different systems of absorption lines at different redshifts in one object. The quasar OF 097 has eight different known redshift systems and the large majority of lines remain unidentified!

These features are not normal stellar absorption features but instead must come from gas that lies between us and the quasar. It must be the atoms in this gas which are absorbing light at their characteristic wavelengths. Since this material has a lower redshift than the quasar does, the absorbing matter must be receding from us at a slower rate. To put it another way, this material is moving *toward* us from the point of view of the quasar. Where is this material located? There are basically two possibilities: (1) The absorption could arise in gas located in an ordinary galaxy between us and the quasar. At high redshifts, the light from the galaxy itself would be too faint to detect; we would only detect the galaxy because it absorbs some of the light from the brighter quasar behind it. This explanation would require that the quasar be at the distance its redshift implies and also that in many cases there just happen to be many galaxies lined up between us and the quasar.

If we know the size of a typical galaxy, then we can calculate how many galaxies one would expect to see between us and the quasar. For example, in only one case out of thirty should a galaxy with a redshift less than 1.0 lie between us and a quasar, if we take the size of the Milky Way galaxy as typical. However, we see many more absorption-line systems than our calculation would indicate could arise from intervening galaxies. This means that either there must be another explanation or that galaxies must be much larger (by a factor of ten) than we have previously believed. While there are some indications that galaxies may have gas at distances well beyond their visible limits, most astronomers would be uncomfortable with requiring a diameter of one million light years for a galaxy like the Milky Way.

(2) Another possibility is that the absorbing material comes from the quasi-stellar object itself, ejected with a high velocity. If this is the case, then quasars are even more remarkable objects than previously believed, because some of the absorbing gas would have to be shot out at

[5]See the article by Don Goldsmith in the Jan/Feb 1977 issue of *Mercury* for more about active galaxies.

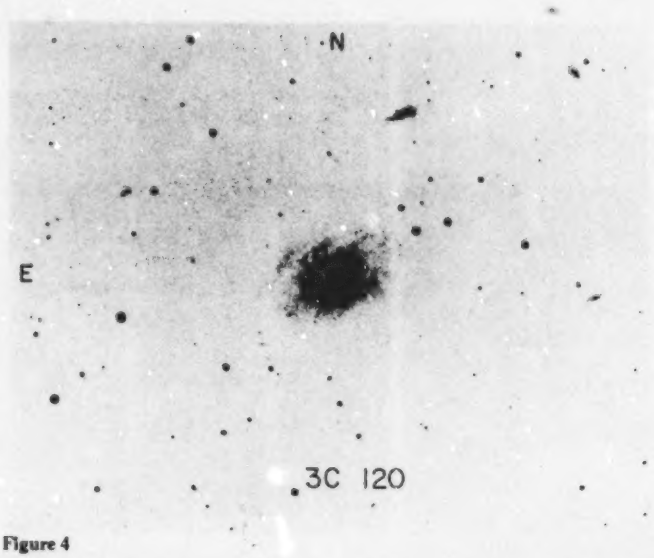


Figure 4

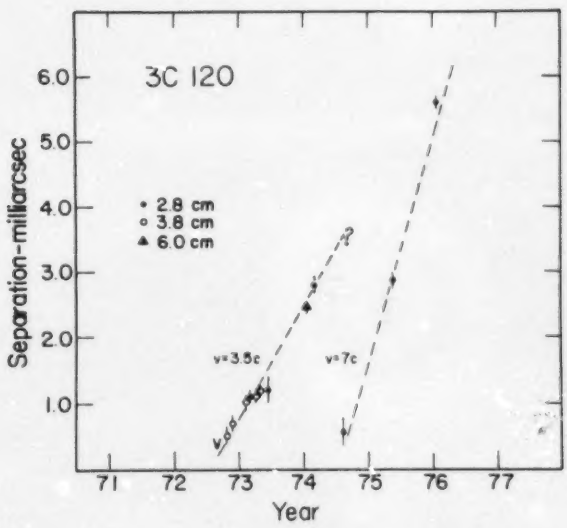


Figure 5

4. The Seyfert Galaxy 3C 120, photographed by H. C. Arp with the Kitt Peak National Observatory 4-meter telescope. The active nucleus of 3C 120 resembles quasars in its strong emission features and variability. A compact radio source in the nucleus of 3C 120 appears to be expanding at a rate faster than the speed of light. (Illustration courtesy of H. C. Arp; reprinted from the **Publications of the Astronomical Society of the Pacific.***)*

5. A plot of the size of the compact radio source in the nucleus of 3C 120 obtained by very long baseline radio interferometry. The two lines represent expansion rates of 3-1/2 and 7 times the speed of light. (Illustration courtesy of K. Kellerman and D. Shaffer and colleagues; reprinted from I.A.U. Colloquium No. 37, CNRS, Paris.)

velocities that are a significant fraction of the speed of light. For example, OF 097 has an emission-line redshift of 2.38, while one absorption-line system in its spectrum has a redshift 0.47. The difference between these two redshifts corresonds to a velocity for the absorbing material of more than 2/3 of the speed of light with respect to the quasar. For such objects, the energy necessary to accelerate clouds to such high velocities may be considerably greater than the energy we see in the form of light of *all* wavelengths.

How could material be driven outward from the quasar with such high velocities? One possibility is that the absorbing material is driven out by radiation pressure. Light waves, when confined to a very small region at great density, will exert a pressure similar to the pressure exerted by a compressed gas. In the central regions of quasars, the energy density of light is enormous, so great that it is possible that material could be expelled with very huge velocities. Radiation pressure is known to be effective in accelerating the shells of gas ejected by galactic novae to speeds of a few thousand kilometers per second. Whether radiation pressure is sufficient to accelerate quasar clouds to relativistic velocities is not certain.

Certainly, in some quasars, we know that absorbing material is being driven out at velocities of 10,000 kilometers per second or more. These quasars show deep broad absorption troughs on the blue side of their emission features. (See for example the spectrum of PHL 5200, shown in Figure 7.) Such broad absorptions could not be the result of an intervening galaxy and must arise from material streaming outward from the quasar. Some astronomers have speculated that as these streams, or winds, of absorbing material are accelerated further, they break up into individual clouds, which form the narrower absorption systems seen in most high-redshift quasars. This again provides an analogy with galactic novae, whose shells appear first as broad absorption features in the nova spectrum, but subsequently break up into narrower systems.

There are also absorption-line systems which seem clearly to be due to intervening galaxies: the most clearcut case is the quasar 3C 232, which shows absorption features in its spectrum from the relatively nearby galaxy NGC 3067. Whether most of the absorption systems can be explained by galaxies or whether one must find a means to eject clouds at very high velocities remains one of the most intriguing questions posed by the quasi-stellar objects.

A Quasar Model

Because of our limited understanding of the physical processes occurring in quasars, we cannot make an accurate, detailed model of them. A crude general picture of a typical quasar[*] can be assembled from all that we have found out, however. From their variability, we know that the central source cannot be more than a few light weeks in size. Considering the shape of their radio and visible light spectrum and the high degree of polarization of the radio and visible light quasars emit, most pundits believe that this region is producing light by the "synchrotron" emission process.

"Synchrotron" radiation is produced by very fast moving electrons spiraling around lines of magnetic force. (The name comes from the large particle accelerators which use magnetic field to accelerate charged particles to very high energies.) A source with a diameter of a few light weeks would need a magnetic field of a few tenths of a gauss (several orders of magnitude stronger than the magnetic field in our galaxy) to explain the synchrotron emission. As the electrons spiral along the magnetic field lines, they lose their energy very quickly by the very act of producing synchrotron emission. One can calculate that even the highest energy particles will radiate all their energy away in a few seconds. This means that the "machine" powering the quasar must continuously supply fresh high-energy electrons throughout the source volume.

Outside the central source of synchrotron radiation lies the hot plasma that produces the emission features in the quasar's visible light spectrum. This region must have a density of around 1 to 10 billion atoms per cubic centimeter and a temperature of about 20,000 degrees centigrade. The line-emitting region is considerably larger than the central source; calculations suggest that it has an extent of about 10 light years. Ultraviolet light from the central synchrotron source is absorbed in this region, ionizing and heating the gas. The broadness of

[*]In the following analysis, we shall assume that the quasars are at cosmological distances.

the emission features is believed to be produced by motions of emitting clouds in this volume. The light emitted by each cloud is redshifted or blueshifted, depending on whether the cloud is moving toward or away from the central source. The combination of all the redshifted and blueshifted emission clouds produces a broad emission feature. Velocities of several thousand kilometers per second are necessary to explain the widths of the emissin features in quasars.

If absorption features *are* produced by the quasar, then the absorbing material must be located outside the line-emitting region. The absence of certain absorption features, which would almost certainly be present if the absorbing material were very close to the central source, requires that at least some of the absorbing clouds be as far as several thousand light years from the active region.

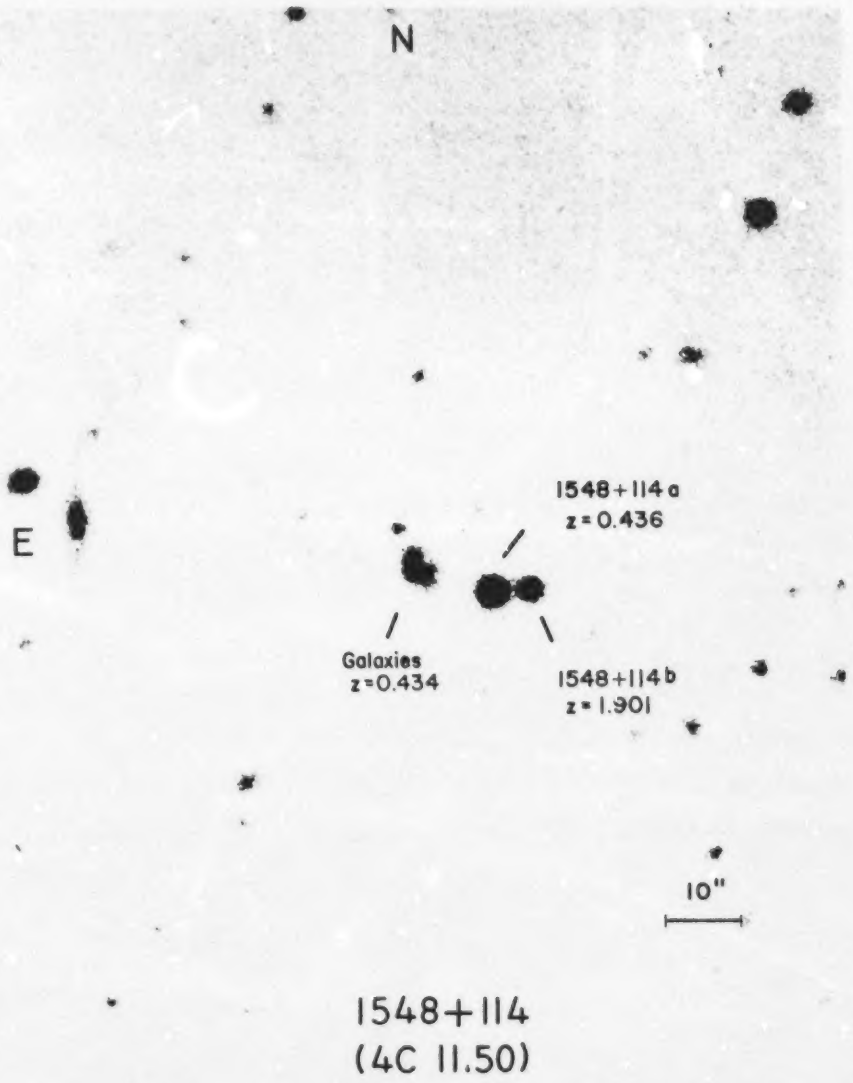
The Energy Source

The difficult search for a plausible source of energy to power the highly luminous quasars has led astronomers to look for smaller scale examples of efficient energy conversion in our own galaxy. One such example is a supernova, the violent death throes of a massive star which releases tremendous amounts of energy in a single consummate gasp (up to hundreds of times the energy output of the Sun in its entire lifetime). Even though supernovae are the most energetic single events we have witnessed, it would take fifteen supernovae a year to power 3C 273. This rate is over a thousand times higher than the supernova rate we currently observe in our own and other galaxies. This discrepancy has led to the speculation that, in massive compact star clusters, collisions between lower mass stars might cause such stars to coalesce and to form many stars massive enough to produce supernova explosions. These explosions, at irregular intervals, might explain the erratic variability of quasars and, under the proper conditions, one explosion might even set off a chain reaction, which could explain outbursts such as the one observed in 3C 279.

The discovery of pulsars,[7] and the efficient way in which the Crab nebula pulsar supplies energy to the nebula, has led to the suggestion that quasars are powered by a very large number of pulsars. This model is related to the previous one in that the pulsars would have to be produced by supernovae, although at a somewhat lower rate than in the first model. A variation on this theme is the speculation that a single, extremely massive (up to 100 million solar masses) rotating star, dubbed a "spinar," might supply the quasars' energy in the form of a magnetic field and energetic particles, like a super-pulsar. One difficulty with this theory is the lack of a fixed periodic variation in the quasars' output like those seen in pulsars. However, it may be that a spinar is hidden so deeply inside the quasar that such variability would not be seen. The detection of regular variability in any quasar would, on the other hand, be a big plus for this theory.

Finally, there is the speculation that quasars might be powered by matter falling into very massive black holes. The current interest in black holes, and the belief that a black hole may have been discovered in the X-ray binary system Cygnus X-1 has made this theory very popular recently. Some astronomers have proposed that a massive black hole might be formed naturally during the gravitational contraction that forms the nucleus of a galaxy.

Even the most speculative of these theories is very hard pressed to provide the necessary energy for the most luminous quasars. Nor at the moment is there any clearcut observational evidence to support one theory over another. It may well be that the best theories to explain quasars are yet to be discovered.



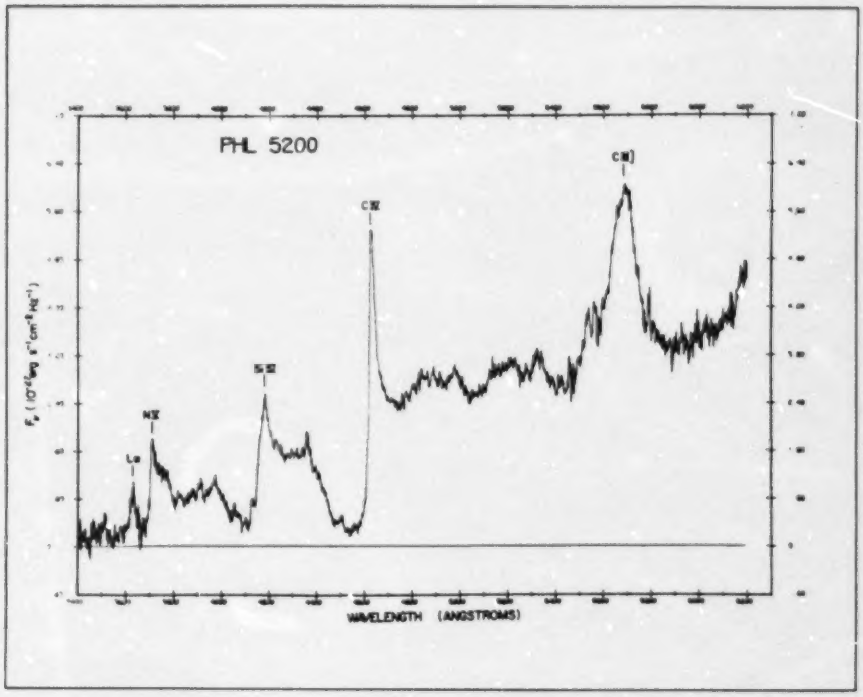
6. A photograph of the region surrounding the pair of quasars named 1548+114, obtained with the Kitt Peak National Observatory 4-meter telescope. Is this a chance occurrence of two objects with very different redshifts simply appearing to be so close together, or could they be physically associated? The brighter quasar, 1548+114a does appear to be associated with a small faint group of galaxies at about the same redshift. (The letter z is a symbol for redshift.)

Future Prospects

Much of the interest in quasi-stellar objects has come from the prospect of using quasars as probes of our universe. We have already noted that the highest redshift

[7]For more on pulsars, see the article by David Helfand in the May/June 1977 issue of *Mercury*.

quasars have "look-back times" that are up to 90% of the age of the universe. Can we use these objects to learn about the universe in its early stages? If it can be established that most of a quasar's absorption lines arise from material at its cosmological distance, or if we can find a way of resolving such absorption systems from other systems associated with the quasar, then the absorption-line spectra may be able to tell us about the abundances and physical conditions in galaxies and protogalaxies at times when the universe was very different. Comparison of absorption systems at different redshifts might allow us to see how galaxies evolve into the systems we see nearby. Another exciting possibility is the suggestion that one may be able to apply corrections to the apparent brightnesses of quasars so as to form a redshift-magnitude diagram from quasars similar to that for galaxies. These diagrams are one of the cornerstones of modern cosmology, permitting astronomers, in theory, to select among different models of the evolution of the universe. In this case, the quasars' large redshifts would allow us to determine the structure of the universe to a much higher precision than has ever been possible. These prospects are very exciting, but it is clear that realizing them will require a much better understanding of quasars than we now possess. ■



7. The spectrum of the quasar PHL 5200. The strong broad troughs to the blue of the emission features are due to absorption by gas streaming out of the quasar with a velocity of about 10,000 kilometers per second.

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Quasars With Fuzz

Bruce Balick
University of Washington

A CCD negative image of quasar 0351+026 and its surroundings. The quasar, one of the four observed by Balick and Heckman, is heavily overexposed in this image, and is the dark oval object slightly above the center. (The small, black square is a detector artifact.) "Fuzz" — which is actually starlight from a host galaxy — can be seen extending roughly five seconds of arc north and south of (above and below) the quasar. Fourteen arc-seconds south of the quasar is a severely distorted companion galaxy with a relatively bright nucleus. The two galaxies are in a common halo of luminous material, which can be seen extending to the right of the companion. The other dark spots in the field are probably foreground stars in our Galaxy. (KPNO photograph courtesy of G.D. Bothun, et al and The Astronomical Journal; © *Copyright 1982, American Astronomical Society)*

Quasars

One of the A.S.P. bumper stickers proudly proclaims the slogan "QUASARS ARE FAR OUT." Ironically, two of the recent A.S.P. Presidents have eloquently argued over the past decade that this statement is more a flawed contention than a scientifically justified statement.

Quasistellar objects (QSO's or quasars) have been at the focus of much astronomical research and controversy since their discovery 20 years ago.[1] Quasars are most clearly distinguished from other kinds of objects by their nearly or completely star-like appearance, their generally blue colors, and by the observed shifts of their spectra compared to all objects we might call "local." Lines in the spectrum of radiation emitted by the quasars show a "redshift" — that is, a shift toward redder colors (for light) when compared to spectra produced in laboratories on Earth.

What Causes the Redshifts

No one contests the wavelength shifts observed in quasars. However, the physical process responsible for the shift is at the center of the "quasar controversy." In the case of ordinary stars and galaxies, shifts in wavelength are universally ascribed to motions (velocities) of the emitting object towards or away from the observer. (Recession implies a redshift, approach a blueshift.) Thus, it might be argued by analogy, the large redshifts of quasars imply that they are receding from us at enormous velocities — in some cases velocities comparable to the speed of light. Many astronomers believe that such enormous velocities of recession can be explained by the expansion of the universe. We know from our observations of galaxies that distant objects recede from an observer faster than nearby ones; therefore, the conventional view has it, many quasars are exceedingly "far out." This view is very popular — but, of course, as Ptolemy's model for the solar system illustrates, popularity is not necessarily a gauge of accuracy. Other explanations for large redshifts can be and have been proposed.

These other attempts to explain the large redshifts of quasars in less traditional ways have been ingenious. For example, it has been suggested that quasars are objects expelled from our galaxy at enormous velocities (and hence redshifts). In this view, quasars lie within a few million light years of the Milky Way, that is, no farther than M31 (the Andromeda Galaxy.) Alternately, it has been suggested that the redshifts of quasars result from some physical process other than motion away from us. It may also be that other physical processes that can cause redshifts have yet to be suggested.

Or, perhaps, the redshifts arise from gravitational effects. The Theory of Relativity predicts that light loses energy — i.e., increases in wavelength — as it propagates away from a region of high gravitational force, such as the surface of a massive object. For the Sun this effect is barely noticeable (wavelengths are increased by 0.0005%); for black holes photon[2] wavelengths increase infinitely. Conceivably, quasars emit their light from just above the surface of a very massive, compact object. Thus their photons could increase in wavelength by factors of 1, 2, 3, or more, depending on the strength of the gravitational forces at the point of photon origin.

A Quasar Model

Since the physical processes at work in quasars are not yet understood, it is difficult to defend any opinion of the cause of quasar redshifts based solely on observation. Nonetheless, speculation abounds. For example, one currently popular idea is that the energy emitted by quasars in the form of light is derived from material as it falls onto a black hole with a mass as large as a billion Suns.[3] If this model is correct, the gravitationally induced redshifts will be significant for light emitted from the quasar.

The massive black holes required for this model are only expected at the centers of galaxies (called "hosts"). Starlight emitted from parts of the host galaxy many thousands of light years

1. Readers not familiar with quasars might want to read two introductory articles which appeared in past issues of *Mercury*: "Quasi-Stellar Objects" by Harding E. Smith (Mar/Apr 1978) and "Cosmic Distances and QSO's" by Joe Tenn (Jul/Aug 1979, plus a follow-up report Sept/Oct 1979.) — *Ed.*

2. Light can be thought of either as a wave or as packets of energy called *photons*. When light is redshifted, that is equivalent in the photon model to each photon losing some energy. — *Ed.*

3. For one explanation for how material falling onto such a supermassive black hole could produce prodigious amounts of energy, see the article by William Kaufmann in the Sept/Oct 1978 *Mercury*. — *Ed.*

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from the massive nucleus will not be subject to any measurable gravitational redshift. Therefore the observed redshifts of a quasar, on the one hand, and the host galaxy around it, on the other hand, could differ substantially. It was with this idea in mind that Tim Heckman and I set out to look for substantial differences in redshift between a quasar and any galaxy around it.

Earlier Observations.

Our results cannot be presented without first mentioning the pioneering observations of several other people. In order to appreciate their results, keep in mind that it is easy to hypothesize that quasars are associated with galaxies, but it is by no means a trivial matter to show this. An inspection of quasars on the Palomar Sky Survey almost always shows star-like images (there are some exceptions, but in those cases the nebulosity associated with quasars takes the form of jets or detached blobs rather than an underlying galaxy). Painstaking imaging programs on large telescopes at sites of excellent atmospheric stability have been conducted over the past few years by many astronomers — John Hutchings, David Crampton, Bruce Campbell, Susan Wyckoff, Peter Wehinger, Alan Stockton, and others — in order to investigate the immediate environment of quasars. These investigators have begun to achieve some success: there are about two dozen cases of quasars surrounded by "fuzz." This fuzz has the general appearance, luminosity, and color of a very distant galaxy. It is from such lists of fuzzy quasars that Tim and I selected a sample for spectroscopic investigation in order to establish whether the fuzz consists of starlight and, if so, to determine the redshift of the fuzz relative to the central quasar.

Our Observations

The fuzz of the quasars is very faint, and conventional spectrographs and detectors on large telescopes are not adequate for investigating its spectroscopic character. For our run, Tim and I used an extremely low loss dispersing element, nicknamed a "grism," to spread out the light and a very efficient solid state detector, a charge-coupled device, or "CCD," to detect it. This spectrograph-detector package is available on the 4-meter Mayall telescope at Kitt Peak National Observatory.

Two nights of telescope time were scheduled, and at sunset of the first night a storm materialized. Early on the second night the clouds broke, but the atmosphere was unstable (stellar images were two to three seconds of arc in diameter). As a result, we could only work with those quasars with the most extended fuzz — a very limited sample indeed. It turned out that only four objects could be observed in the time available.

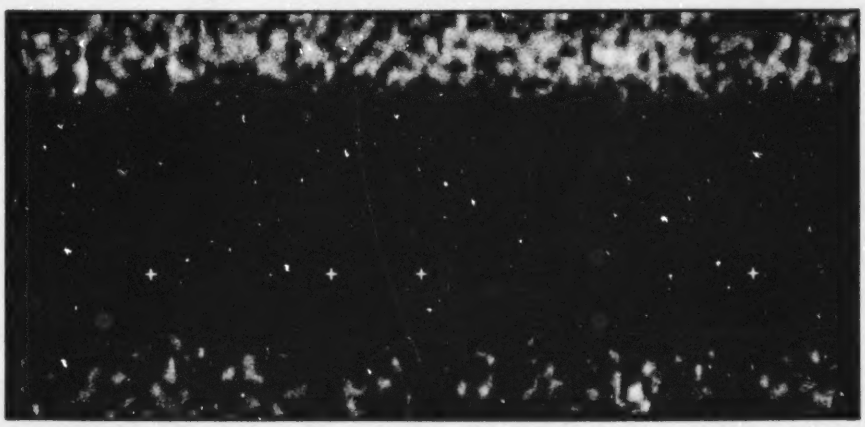
Three of the four fuzzy quasars observed yielded two positive results: the fuzz around the quasar is spectroscopically identical to starlight from ordinary galaxies and the redshifts of the stellar lines and those of the quasar lines are essentially identical (to within a percent or less). Subsequent observations using the same instrument indicate that the fourth object is very similar to the other three.

Interpretations

The results show that the redshifts of the four quasars and those of the associated host galaxies arise from the same physical process, whatever that process may be. Since a local gravitational origin of *host galaxy* redshifts appears to be an unlikely explanation, that process cannot be responsible for the redshifts of the embedded quasars. The same thing holds true for models involving an ejection from the Milky Way. A cautionary note: the observations do *not* prove that redshifts of quasars necessarily arise from the expansion of the universe. On the other hand, it is commonly accepted that the redshifts of galaxies originate from cosmological velocities of recession, and on this basis we feel that the simplest, most straight-forward interpretation of our observations is that the four host galaxies — and the quasars associated with them — are indeed far out.

But it is premature to conclude, based on our observations, that all quasars derive their redshifts from universal expansion. First, we must keep in mind the small size of our sample and the associated narrow criterion we used to select our objects. Second, the quasars studied span the range of 0.04-0.4 in redshift — not a large range. If only some portion of a quasar's redshift is related to causes other than distance, then one expects the largest quasar-fuzz redshift differences to be observed in systems of highest quasar redshift. These quasars have not been extensively surveyed to see if they are surrounded by fuzz. Until this step has been taken, the critical spectroscopic observations cannot be attempted and the really interesting and fundamental questions of physics cannot be decisively addressed.

The quasar controversy — the question of which process is responsible for the large redshifts of quasars — has been tumbling through astronomy for a generation. The controversy had become a little more subdued lately, primarily because little new information had been generated for several years. The recent important imaging and spectroscopic observations have now added new weight to the bin of observations that are consistent with the notion that the redshifts of quasars arise from the expansion of the universe. However, consistency does not constitute proof. Until decisive observations are available the controversy will linger and stimulate (provoke?) further interesting research projects. ■



Portion of a spectrum obtained for quasar 0351+026 and its companion using the new "cryogenic camera" and the 4-meter Mayall telescope at KPNO. The heavy black horizontal line is an overexposed spectrum of the quasar on this negative image. Crosses mark the positions where — in more moderate exposures — bright lines in the spectrum of the quasar and an absorption feature due to magnesium in starlight of the host galaxy's "fuzz" appear. Above the overexposed quasar spectrum is the spectrum of the faint, distorted companion galaxy. Above the leftmost cross is an absorption line, due to hydrogen, which arises in the galaxy's starlight; analysis of the spectra shows that the redshift of the quasar and its companion are essentially the same. Connecting the quasar and companion is a region in which an emission line of oxygen arises, seen at the center of the figure. (KPNO photograph courtesy of Bruce Balick.)

4C18.68: A Quasar with Precessing Jets?

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and

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Ever since their discovery some twenty years ago, quasars have remained one of the most exotic and puzzling types of object in the universe. From their enormous redshifts we judge them to be the most distant and luminous objects we can see. More mysteriously, their ability to change brightness in a short time indicates that they are very small—perhaps on the order of the size of the solar system—yet radiating more power than our entire Galaxy.

Recent optical imaging with the world's finest telescopes and detectors has shown that the nearer quasars, at least, appear to lie at the centers of fuzzy objects that have some characteristics of galaxies, and that they have as neighbors fainter galaxies. Thus, quasars may be active nuclei residing at the centers of galaxies, which for some reason achieve prodigious outputs of energy (from X-ray to radio wavelengths), perhaps only for a short era in the lifetime of their host galaxies. A favorite energy source which seems able to achieve this is a massive black hole (say 100 million solar masses), perhaps formed from the dead bodies of early generations of stars in the galaxy's lifetime.[1]

Indeed, a study of the redshifts (hence ages) of quasars shows that most of them lived (and presumably died) long ago[2]. This, in our picture, might correspond to the central engine using up most of its available fuel—gas and first-generation stars—in the early days of the life of the galaxy. Allowing all this, the puzzle remains as to why some quasars still exist in the nearby (i.e. present epoch) universe, long after galaxies have formed and converted their gas into stars which never approach the centers of galaxies (where the quasar "engine" would be located).

A striking new clue to this puzzle may lie in some of the detailed radio "pictures" being produced at the National Radio Observatory's Very Large Array, a group of 27 large radio telescopes near Socorro, New Mexico. This array is able to discern detail in the structure of quasars smaller than one arcsecond[3]. At radio wavelengths a number of quasars are found to have

1. For more about this explanation, see the article by William Kaufmann in the Sep/Oct 1978 issue of *Mercury*. — *Ed.*

2. Because light takes time to reach us, as we look farther out in space, we are looking farther back in time. Since most quasars are seen at high redshifts (which correspond to great distances in the conventional view of these objects) we are seeing objects as they were long ago. — *Ed.*

3. An arcsecond is 1/3600th of a degree or roughly the size of a U.S. dime as seen from a distance of 2 kilometers. — *Ed.*

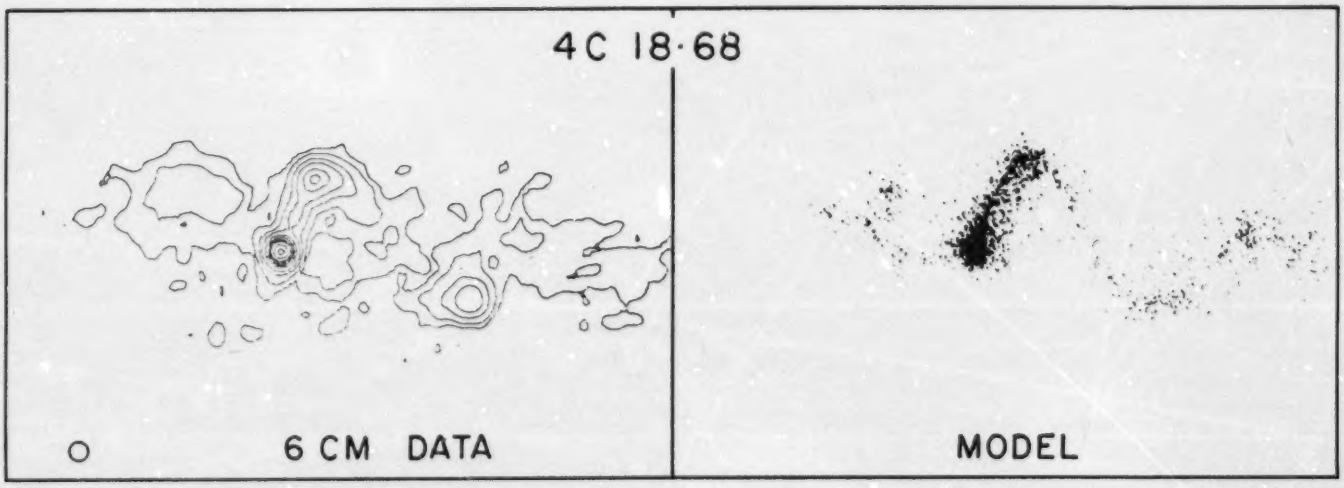

Figure 1. The left panel shows the radio intensity contour map of 4C14.68 made at a wavelength of 6 cm with the VLA. The visible quasar lies at the position of the intense point source near the middle. The width of the picture is 12 arseconds. The right panel shows the prediction of the computer generated model of precessing jets which best fits the observed radio structure. In this picture, the density of dots represents the radio intensity, and compares well with the real observations shown on the left.

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some rather bent, or even wiggly, structure extending from their brilliant nuclei. These extensions are characteristically somewhat larger than the quasar's host galaxy.

A recently-discovered striking example is the quasar 4C18.68, shown in the illustrations. This radio source is relatively nearby, having a redshift 0.31, and the visible object that corresponds to it is known to be fuzzy. The continuity of the radio structure, and its detailed characteristics, such as its polarization and spectral index, strongly suggest that we have a snapshot of a radio jet whose direction wobbles about during the lifetime of the emission we see. We can in fact go much further than this. It is possible to model the radio structure of 4C18.68 with a relativistic jet of matter whose direction is precessing in the sky like the axis of a top. In this model, the material is actually ejected in two opposing jets, but because of relativistic effects, the main part of what we see is the jet coming towards us. Two effects contribute to this: a) the intensity is enhanced in the forward direction so that the approaching jet appears brighter, and b) light travel time across parts of the structure (some thousands of light years across) causes apparent distortions in the geometry, in particular stretching the approaching jet pattern compared with the receding one. Our illustration shows the model which best fits the observed picture. In this model the velocity of the jet is 70% of the speed of light.

The agreement between a model and observations in a single case may be fortuitous rather than meaningful. However, this quasar is only one of several which can be modelled in this way. Therefore we may speculate a little further.

The precession of such a jet is likely to arise from the close orbital motion of two massive bodies whose spin axes do not point in the same direction. This is the proposed mechanism at work in the bizarre binary star SS433 in our own galaxy.[4] If we were to suppose that a similar situation has arisen in these bent radioquasars, we have a new possible scenario for the existence of nearby quasars. If a long dead quasar encounters another galaxy, and the encounter is close enough that the two galactic nuclei form a bound orbiting pair, we may power up the quasar by feeding it gas or even stars brought close enough by the encounter. Furthermore, the gravitational interaction of the two galactic nuclei may cause precession of the radio jets from the active nucleus. The precession periods implied by the models are of the order of 10,000 years, and these are consistent with the central masses considered likely for quasars. The whole phenomenon may well be a short-lived one, so that the universe could be full of dead or latent quasars, which can regenerate for a few million years when disturbed in this way. Investigations are now focusing on ways of checking the predictions and consistency of these ideas, and of understanding why some objects are quasars and others are not. Whatever the final story, it seems likely that objects like 4C18.68 will provide important clues to our understanding of quasars and their evolution. ■

4. For more on SS433, see the article by Bruce Margon in the Sep/Oct 1979 issue of *Mercury*. —*Ed.*

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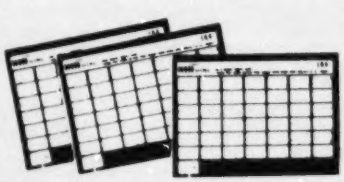

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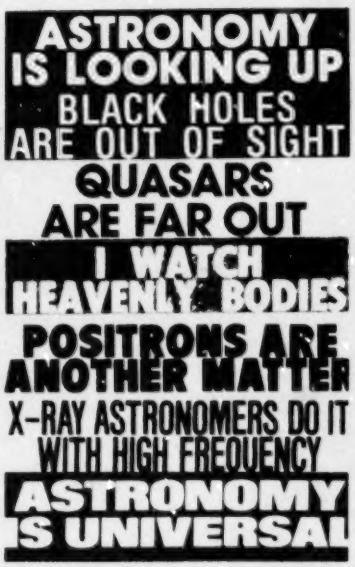
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Quasars: A Selected Nontechnical Bibliography

by Andrew Fraknoi

Astronomical Society of the Pacific

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